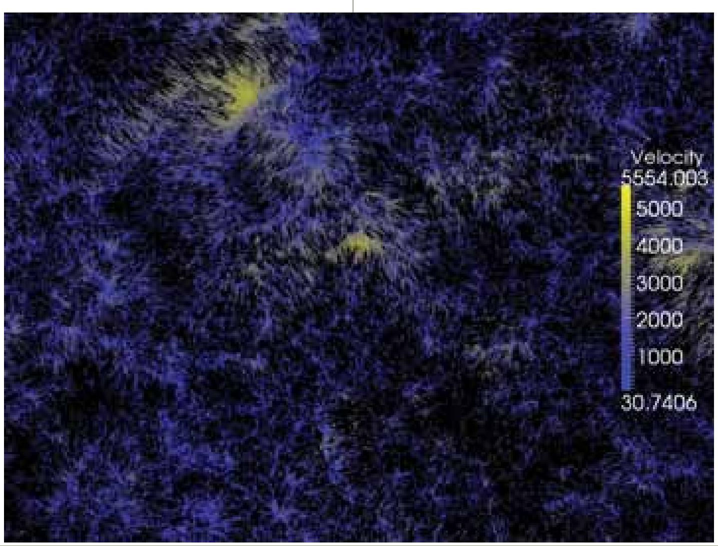
The Roadrunner Universe Project: Baryon Acoustic Oscillations in the Intergalactic Medium

Adrian Pope, ISR-1/T-2/CCS-6; Katrin Heitmann, ISR-1; Salman Habib, Zarija Lukić, T-2; Patricia Fasel, CCS-3; David Daniel, CCS-1; Martin White, Jordan Carlson, University of California, Berkeley

Fig. 1. Dark matter halos from one of the large Roadrunner simulations, with 1/64 of the total (750Mpc/h)^3 volume displayed. The halos are shown as arrows, colored with respect to their velocity magnitude. This particular simulation was run with 64 billion particles, where each simulation particle has a mass of approximately one billion suns. The snapshot is taken at a redshift of z =2.5.



Over a decade ago, supernova observations first suggested that the expansion rate of the Universe was accelerating; this result has now been verified by a number of observations. The acceleration can either be driven by a mysterious source in the Einstein equations, the dark energy with a negative equation of state, or may hint at possible modifications of general relativity. Current datasets, while agreeing on the fact of the acceleration, only constrain the equation of state to about 10% [1]. At this level of accuracy, the acceleration could be explained by a cosmological constant – perfectly acceptable classically, but severely incompatible with quantum estimates by many orders of magnitude.

More accurate observations are needed to decide whether the equation of state is time variable (which would rule out a cosmological constant), or whether general relativity is valid on very large cosmic scales. It turns out that the formation of structure can be an excellent probe of the evolutionary history of the Universe. Moreover, by tracking the growth of structure one can also test whether the predictions of general relativity are valid. For these reasons, cosmological probes based on structure formation dominate discussions of precision cosmology, targeting accuracy levels of 1% or better.

Analytical methods are of limited use at this level of accuracy, and one must resort to numerical simulations. To meet this challenge, a new hybrid petascale code has recently been developed by us at LANL, under the aegis of the Roadrunner Universe (RRU) project [2]. The code was tested and run on Roadrunner during the recent Open Science period when the full machine was made available to a select number of application codes.

The Open Science RRU run on Roadrunner consisted of nine ultra-large simulations to study the imprint of oscillations in the baryon-photon plasma in the early Universe, the Baryon Acoustic Oscillations (BAO). Due to BAO, a distinct but subtle signature is imprinted on the large-scale distribution of matter and has been seen in the spatial statistics of the distribution of galaxies [3], confirming one of the most important predictions of modern cosmology. BAO has now become one of the premier methods for determining cosmological distances, and hence, the expansion history of the Universe.

Traditional galaxy-based BAO surveys require a heavy investment in telescope time, especially as one goes to higher redshifts. Fortunately, tracers of the mass distribution, other than galaxies, exist. Neutral hydrogen in the intergalactic medium (IGM) furnishes one such example. At redshifts of $z \cong 2$–3, the gas making up the (IGM) is thought to be in photoionization equilibrium, resulting in a tight density-temperature relation, with the neutral hydrogen density proportional to a power of the baryon density [4]. Since pressure forces are subdominant, the neutral hydrogen density closely traces the total matter density on large scales. The neutral hydrogen density can be probed by obtaining spectra of distant, bright compact sources–the quasars–and studying the celebrated Lyman-α forest of absorption lines that map the neutral hydrogen along the line-of-sight to the quasar. The structure in quasar absorption thus traces, in a calculable way, slight fluctuations in the matter density of the universe back along the line-of-sight to the quasar, with most of the Lyman-α forest arising from overdensities of a few times the mean density.

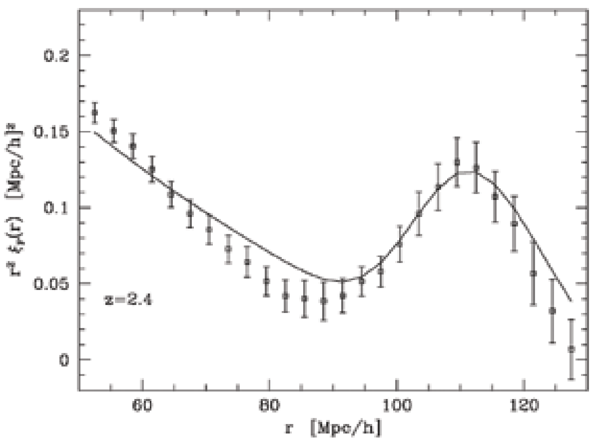


Fig. 2. The redshift space flux correlation function, ξ_F, as a function of the co-moving distance, r, measured in Mpc/h. The BAO feature is the bump centered around 110 h^{-1} Mpc. The error bars are derived from a bootstrap analysis. The solid line is a Gaussian-smoothed linear theory result multiplied by a scale-independent bias to match the simulations.

The upcoming Baryon Oscillation Spectroscopic Survey (BOSS) [5] will provide an unprecedented number of quasar spectra for Lyman-α studies, motivating a major simulation effort at understanding the BAO imprint in the IGM. The set of Roadrunner simulations [6] are the first to simultaneously resolve structure down to the Jeans scale of the gas ($\cong$ 100 kpc), as well as properly capture the acoustic scale ($\cong$ 100 Mpc). Using the results of the simulations (the density and velocity fields), mock quasar spectra were constructed by running lines of sight from quasar sources to an observer. These spectra have properties close to those observed at $z \cong 2$–3. Because these mock spectra will be very useful in testing observational data pipelines, calibrating analysis tools, and in planning future projects, they have been made publicly available.

Given the quasar spectra derived from the simulations, one can compute the flux-flux correlation function, which is related to the underlying nonlinear, redshift-space, mass correlation function. The characteristic BAO bump signal in the flux correlation function, as measured from our simulations, is shown in Fig. 2. Although our total simulation volume is large (nine 750h^{-1} Mpc boxes), covering effectively 1000 sq. deg. of sky, it is still only 10% of the area planned for BOSS. Thus the fractional errors in the flux correlation function as achieved by BOSS should be better than in our simulations by a factor of three.

Once detailed simulations are available, several important effects can be studied, including key sources of systematic errors and bias in the observations. We carried out preliminary investigations of an evolving mean flux, fluctuations in the photoionization rate, and HeII reionization, which generate extra power on the acoustic scale and reduce the contrast of the acoustic peak. Gravitational instability produces a well-defined pattern of higher-order correlations that is not obeyed by nongravitational contributions such as the above, allowing, in principle, a diagnostic of nongravitational physics in the forest. As an example, we demonstrated that the three-point cross-correlation function in models with HeII reionization has a different scale dependence than the three-point function in gravity-only simulations, regardless of the equation-of-state assumed in the latter.

As one part of the Roadrunner Universe project, future BAO simulations will be run with much larger boxes for an improved treatment of planned surveys. Additionally, the quasars will not be randomly placed in the simulation box, but will follow the appropriate statistical occupation distribution for being hosted by dark matter halos.

For more information contact Salman Habib at habib@lanl.gov.

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